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Investigating the efficacy of neurofeedback training for expediting expertise and excellence in sport

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ABSTRACT

Objectives: This experiment examined whether electroencephalographic (EEG)-based neurofeedback could be used to train recreational golfers to regulate their brain activity, expedite skill acquisition, and promote robust performance under pressure.
Design: We adopted a mixed-multifactorial design, with group (neurofeedback, control) as a between-subjects factor, and pressure (low, high), session (pre-test, acquisition 1, acquisition 2, acquisition 3, post-test), block (putts within each training session), and epoch (cortical activity in the seconds around movement initiation) as within-subject factors.
Methods: Recreational golfers received three hours of either true (to reduce frontal EEG high-alpha power, $N = 12$) or false (control, $N = 12$) neurofeedback training sandwiched between pre-test and post-test sessions during which we collected measures of cortical activity (EEG) and putting performance under both low and high pressure conditions.
Results: Individuals in the neurofeedback group learned to reduce their frontal high-alpha power before striking putts. Despite causing this more "expert-like" pattern of cortical activity, neurofeedback training failed to selectively enhance performance, as both groups improved their putting performance similarly from the pre-test to the post-test. Finally, both groups performed robustly under pressure.
Conclusions: Performers can learn to regulate their brain activity using neurofeedback training. However, research identifying the cortical correlates of expertise is required to refine neurofeedback interventions if this training method is to expedite learning. Suggestions for future neurofeedback interventions are discussed.

Optimisation of performance is a lengthy process for novice learners who wish to become expert performers. Our goal as researchers is to develop and refine methods to shorten this training and in the process equip learners with the skills to perform under pressure. Theories of motor control contend that expert-like performance depends on accurate programming of movements during the final stages of preparation for action (e.g., Keele, 1968). These theories are supported by research that uses electroencephalography (EEG) to assess cortical activity during movement tasks (Cooke, 2013). Experts typically exhibit greater cortical specificity compared to novices when planning and executing movements, such as reduced activity in the verbal-analytic left temporal regions (e.g., Hatfield, Haufler, Hung, & Spalding, 2004). Moreover, novices show evidence of increasing cortical specificity during practice as they refine the motor skill, such as a progressive reduction in left-temporal activation (e.g., Landers et al., 1994), as they advance along the skill acquisition continuum. Building upon this evidence, it has been suggested that the acquisition of psychomotor skills might be enhanced by training individuals to emit the pattern of cortical activity associated with successful psychomotor performance (Cooke, 2013). However, the evidence to date is extremely limited. Although there are case studies of elite athletes claiming that EEG-based neurofeedback training helped them perform optimally, there are few published experiments to corroborate these claims.

The ability to acquire and master new skills quickly is crucial in many domains, including the armed forces, the emergency services,

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and sport. In order to expedite learning, some organisations employ the latest state-of-the-art brain-computer-interface systems to deliver neurofeedback training (Zaichkowsky, 2012). This technique involves teaching novice performers to produce patterns of cortical activity that characterise well-seasoned experts. The rationale for such training is that, theoretically, it speeds up learning by directly encouraging the development of neural patterns that normally take many years to evolve. However, in spite of the growing popularity of neurofeedback training in applied settings, empirical investigations of its efficacy for expediting expertise in sport are scarce. To fill this void in the existing literature, the aims of this experiment were to: a) evaluate whether neurofeedback training could teach recreational golfers to produce the patterns of brain activity characteristic of experts in the moments preceding putts; b) examine whether neurofeedback training could improve performance, thereby accelerating the evolution from novice to expert; and, c) evaluate whether neurofeedback training could help produce patterns of cortical activity and performance levels that would be robust to the potential deleterious effects of increased psychological pressure.

Neurofeedback training in sport

Neurofeedback training provides individuals with real-time information about their level of cortical activity via sounds or visual displays (Hammond, 2007). Based on principles derived from operant learning theory (e.g., Skinner, 1963), rewarding positive reinforcement, such as a change in the pitch of a tone, is provided when a desired level of cortical activity is achieved. Electroencephalography (EEG) is perhaps the most common brain imaging method that is used to provide neurofeedback training (e.g., Vernon, 2005). In brief, EEG involves the recording of electrical activity on the scalp to detect voltages generated in the brain. EEG offers exquisite temporal resolution, whereby changes in activation are detected more or less instantaneously (e.g., Harmon-Jones & Peterson, 2009). Moreover, EEG can be measured while participants stand and perform a range of movements, which makes the method particularly well suited for providing neurofeedback in sport (e.g., Thompson, Steffert, Ros, Leach, & Gruzelier, 2008).

To this end, there have been a handful of studies investigating whether EEG neurofeedback training can facilitate performance in sport, and while the evidence concerning the effectiveness of EEG neurofeedback is not conclusive, it is certainly encouraging (e.g., Arns, Kleinnijenhuis, Fallahpour, & Breteler, 2007; Kavussanu, Crews, & Gill, 1998; Landers et al., 1991; Rostami, Sadeghi, Karami, Abadi, & Salamati, 2012). For instance, the seminal study of neurofeedback in sport was conducted by Landers et al. (1991), and investigated the effects of neurofeedback in sixteen experienced archers. Landers et al. (1991) reasoned that archery performance should be associated with activation of the right-hemisphere of the brain, which is associated with visual-spatial processing, and deactivation of the left-hemisphere of the brain, which is associated with verbal-analytic processing (e.g., Hatfield, Landers, & Ray, 1984; Landers et al., 1994). Accordingly, they measured EEG activity and archery performance in pre- and post-test sessions, separated by approximately 60 min of neurofeedback training during which the archers watched their relative left- and right-hemisphere activity on a visual display. Results revealed that performance improved from the pre-test to the post-test in eight archers who were rewarded when they reduced cortical activity over their left-hemisphere. In contrast, performance deteriorated in the remaining eight archers, who were rewarded when they reduced cortical activity over their right-hemisphere.

Although this finding implies that neurofeedback training could be used to expedite learning in archery, it is important to note that left-hemisphere cortical activity in the pre- and post-test sessions was the same for members of both neurofeedback groups. This indicates that the neurofeedback training protocol did not cause members of the left-hemisphere neurofeedback group to suppress left-hemisphere function. Consequently, the improvement in performance that was achieved by this group may not be directly attributable to the neurofeedback that they received.

A more recent study of neurofeedback training by Rostami et al. (2012) also adopted a pre- and post-test design to increase the power of the sensory motor rhythm (i.e., cortical activity between 13 and 15 Hz) over central motor areas (i.e., C3 electrode site) of the brain. Specifically, twelve experienced marksmen attended 15 h of laboratory sessions spread over five weeks, and were trained to control their cortical activity by sitting and watching this activity on a screen. Results revealed that neurofeedback training led to marginal improvements in shooting accuracy from the pre-test to the post-test, whereas the performance of a control group who received no neurofeedback training was unchanged.

While this finding is also supportive of neurofeedback as a tool to aid the development of expertise and excellence in sport, the study was subject to two principal limitations. First, the choice to train participants to increase the sensory motor rhythm over central motor areas was somewhat arbitrary, with the authors providing no theoretical or empirical rationale to support this key methodological feature. Second, no measures of EEG activity were obtained during the pre- and post-test sessions. Accordingly, it was impossible to evaluate whether the beneficial effects of neurofeedback training were attributable to participants having learned to control their patterns of cortical activation.

Finally, perhaps the most informative neurofeedback study in sport was conducted by Arns et al. (2007). They adopted a crossover design in which six amateur golfers completed 12 blocks of putts. The golfers putted as normal in the odd-numbered blocks, and putted while receiving auditory neurofeedback training in the even-numbered blocks. Importantly, the element of cortical activity that was fed back to participants was partly customised to the task. Specifically, a comparison of cortical activity associated with the best (i.e., holed) and worst (i.e., missed) putts during a baseline session was conducted to customise the neurofeedback for each participant. This resulted in participants being trained to reduce a combination of theta (4–8 Hz), alpha (8–12 Hz), sensory motor rhythm (13–15 Hz) and/or beta (15–30 Hz) power in the final moments preceding putts. It is also important to note that the auditory neurofeedback tone was played to participants while they stood over the ball and prepared to execute putts. By adopting these innovative design features, Arns et al. (2007) were the first researchers to provide customised, concurrent neurofeedback training during task performance. Their results revealed that participants holed more putts during the blocks in which they received neurofeedback compared to those in which they did not.

Although this study provides arguably the strongest support for the efficacy of neurofeedback training as a tool to foster expertise and excellence in sport, it nonetheless suffers from key limitations, including low sample size and no control group. Thus, the results of the Arns et al. (2007) study may simply reflect a placebo effect whereby improved performance was elicited by the presence of the neurofeedback system and auditory tone, rather than by changes in cortical activity per se.

The cortical correlates of expertise in golf

Since the work of Arns et al. (2007), two studies have systematically examined the patterns of cortical activity that underpin successful golf putts, and the results of these studies could form the empirical grounding for new neurofeedback interventions.

Specifically, Babiloni et al. (2008) compared patterns of EEG activity characterising holed putts and missed putts in a sample of expert golfers. They found a widespread reduction in EEG alpha power during the four seconds preceding putts. This is consistent with the well-established finding that voluntary self-paced movements are preceded by a reduction (i.e., desynchronisation) in EEG alpha power (around 8–12 Hz) in both hemispheres of the brain during bimanual tasks (e.g., Leocani, Toro, Manganotti, Zhuang, & Hallett, 1997; Pfurtscheller & Aranibar, 1979). Crucially, Babiloni et al. (2008) also found that compared to missed putts, holed putts were characterised by a greater reduction in high-alpha power (10–12 Hz) at sites overlying the premotor and motor cortex (e.g., Fz, Cz, C4), indicating that these sites and the high-alpha frequency band are ideal candidates to be targeted by neurofeedback interventions.

Second, the study by Babiloni et al. (2008) was recently replicated and extended by Cooke et al. (2014). Specifically, Cooke et al. (2014) compared cortical activity preceding holed versus missed putts, in both experts and novices. The results showed that expert golfers displayed a greater reduction in high-alpha power than novices, and that holed putts were characterised by less high-alpha power than missed putts, at frontal and central sites (e.g., Fz, F3, F4, Cz) in the two seconds preceding movement. In sum, the results of Babiloni et al. (2008) and Cooke et al. (2014) provide consistent evidence that expertise and optimal golf putting performance is characterised by a suppression of EEG high-alpha power in the final moments preceding movement initiation.

The present study

To address the limitations of previous studies, the present experiment was designed to be the largest neurofeedback investigation to date, while also being the first to employ concurrent, empirically grounded neurofeedback along with an active control group. Our empirically guided neurofeedback was based on the results of Babiloni et al. (2008), and Cooke et al. (2014), and aimed to teach participants to reduce their frontal high-alpha power before striking putts. Importantly, we also investigated the effects of neurofeedback training on performance under pressure. Previous research has demonstrated that increases in psychological pressure can disrupt patterns of physiological activity during motor preparation and cause impaired performance (e.g., Cooke, Kavussanu, McIntyre, & Ring, 2010; Weinberg & Hunt, 1976). Consequently, our experiment is the first to examine whether neurofeedback training can help performers produce consistent physiological responses which could ensure robust performances across both low and high-pressure conditions.

We hypothesised a series of interactions in which the neurofeedback group would display greater reductions in pre-movement high-alpha power, and greater improvements in performance, from a pre-intervention test to a post-intervention test, when compared to a control group. We also expected individuals in the neurofeedback group to produce consistent patterns of cortical activity and robust performances across both low- and high-pressure conditions during the post-intervention test.

Materials and methods

Participants

Twenty-four right-handed male golfers volunteered to participate in the experiment, and were randomly assigned to a neurofeedback training group ($N = 12$, M age = 23.00, $SD = 5.83$ years, M golf handicap = 23.00, $SD = 6.62$) or a control group ($N = 12$, M age = 21.00, $SD = 2.52$ years, M golf handicap = 23.33, $SD = 4.62$). All participants provided informed consent before taking part.

Task

Participants used a standard length (90 cm) blade style golf putter (Titleist Scotty Cameron Circa 62) to putt regular-size golf balls (diameter 4.7 cm) towards a standard-size hole (diameter 10.8 cm) from a distance of 2.4 m. The hole was located 1.25 m from the end and 0.75 m from the sides of a flat artificial putting surface (Turftiles), which had a stimpmeter reading of 3.05 m (i.e., a medium-to-fast paced green).

Design

We adopted a mixed-multifactorial design. Participants attended a pre-test and a post-test (hereafter referred to as the test phase of the experiment), which included both low- and high-pressure conditions. They also attended three training sessions following the pre-test and preceding the post-test (hereafter referred to as the acquisition phase of the experiment); each session consisted of twelve 5-min blocks of putts. Our design therefore included group (neurofeedback, control) as a between-subject factor, as well as pressure (low, high), session (pre-test, acquisition 1, acquisition 2, acquisition 3, post-test), block (referring to each 5-min block of putts within the training sessions), and epoch as within-subject factors. Epoch refers to the time-windows around movement in which cortical activity was assessed (i.e., −4 to −3 s, −3 to −2 s, −2 to −1 s, −1 s to 0 s, 0 s to +1 s). The inclusion of this factor was in keeping with previous studies (e.g., Babiloni et al., 2008; Cooke et al., 2014). Further details are provided in the data reduction and statistical analyses sections below.

Neurofeedback training protocol

During the acquisition phase of the experiment, participants in the neurofeedback group received three 1-h sessions of neurofeedback training. Cortical activity was recorded from the Fz site on the scalp using an active electrode connected a DC amplifier (Brainquiry PET-4), with reference and ground electrodes attached to the right and left mastoids, respectively. We decided to provide feedback at the Fz site because this site has been shown to capture the strongest differences in high-alpha power between experts and novices and successful and unsuccessful outcomes in the moments preceding golf putts (Cooke et al., 2014). In tandem with cortical recordings, a computer running Bioexplorer software (Cyberevolution) extracted high-alpha power from the EEG signal, and fed this back to participants in the form of an auditory tone. Importantly, the tone was programmed to vary in pitch based on the level of high-alpha power. Moreover, the tone was set to turn off completely (i.e., be silenced) when the following criteria were met: a) high-alpha power was reduced (relative to each participant's individual baseline) by 26.8%, 53.6%, and 80.4% in the first, second, and third training sessions, respectively; b) theta power was reduced (relative to each participant's individual baseline) by 18.2%, 36.4%, and 54.6%, in the first, second, and third training sessions, respectively; c) impedance was low, as reflected by <10 μV of 50 Hz activity in the signal (Arns et al., 2007); d) eye-blinks were absent, as detected by an active electrode that was placed over the orbicularis oculi muscle of the right eye. Participants were required to reduce theta power alongside high-alpha power because theta power at the Fz site has been revealed as an additional marker of expertise in the moments preceding golf putts (Cooke et al., 2014).

The high-alpha and theta power threshold values initially were based on the performance of experts (Cooke et al., 2014) but

subsequently were refined in pilot testing. They were designed to encourage gradual development of participants' ability to reduce high-alpha power, with the thresholds in the final training session roughly corresponding to the reductions in power that characterised the successful putts of experts in previous studies (i.e., Babiloni et al., 2008; Cooke et al., 2014). In line with the study by Arns et al. (2007), the neurofeedback tone was turned off completely for 1.5 s once the neurofeedback thresholds had been reached, except for when high-impedance or an eye-blink was detected within this dwell-period, in which case the tone re-started immediately. Auditory neurofeedback was provided to participants in twelve 5-min blocks per training session *while* participants practiced putting (i.e., concurrent). Specifically, participants were instructed to execute putts when they felt ready, but only when the tone was turned off (i.e., indicating that high-alpha power had been reduced).

Participants in the control group followed an identical procedure to those in the neurofeedback group, except the tone that they heard was not based on their brain activity. Instead, participants in this group were played a recording of the tone from a matched (i.e., yoked) participant in the neurofeedback group. This feature ensured that the tone was turned off on the same number of occasions and for the same duration in both groups, and guaranteed that a similar number of putts were completed by both groups of participants during the acquisition phase of the experiment.

Pressure manipulation

Two pressure conditions (each consisting of 50 putts) were manipulated in the test phase of the experiment using social evaluation, competition, and rewards (Baumeister & Showers, 1986), with the order of the conditions counterbalanced across participants. The two conditions are described below.

Low-pressure condition

This condition was non-competitive, contained no rewards, and was designed to minimise any pressure that may have been elicited by social evaluation. Specifically, participants were informed that performance would be assessed by the average distance of putts from the hole, with holed putts counting 0 cm in the calculation. Crucially, participants were also told that although the accuracy of each putt would be recorded, their individual performance would not be analysed. Instead, it was explained that the performance of all participants would be pooled to generate one accuracy score for the sample as a whole.

High-pressure condition

The high-pressure condition was set up as a competition that offered rewards, and placed an explicit emphasis on social evaluation. Specifically, participants were informed that they would be individually evaluated in this block of putts. To this end, they were told that all participants would be ranked on a leaderboard based on their average distance from the hole in this condition. Moreover, they were informed that the leaderboard would be emailed to all participants at the end of the study, and that cash prizes of £50, £25, £10 and £5 would be awarded to the top four performers (e.g., Wilson, Smith & Holmes, 2007). Finally, they were told that twenty-four participants were to be recruited for the study, allowing each individual to evaluate their chances of winning a prize (e.g., Cooke et al., 2010).

Measures

Acquisition phase

Number of putts struck

We recorded the number of putts struck during each block in the acquisition phase of the experiment. The purpose of this measure was twofold. First, it allowed us to identify and control for possible group differences in the number of putts (i.e., practice) during skill acquisition. Second, we were able to indirectly assess the extent to which participants in the neurofeedback group learned to produce the desired high-alpha power profile, with better control of cortical activity being indicated by more putts being struck per 5-min block.

Performance

Mean radial error (i.e., the mean distance of the balls from the hole) was recorded as our measure of performance (Cooke et al., 2010; Cooke, Kavussanu, McIntyre, Boardley, & Ring, 2011). Zero was used in the calculation of mean radial error on trials where the putt was holed (Hancock, Butler, & Fischman, 1995). Mean radial error scores were obtained by taking a photograph of the final position of each putt using a digital camera (Sony Handycam) suspended above the hole. Photographs were then analysed offline using custom developed "ScorePutting" software (see Neumann & Thomas, 2008).

Test phase

Pressure manipulation check

The 5-item pressure/tension subscale of the Intrinsic Motivation Inventory (Ryan, 1982) was used to test the effectiveness of our pressure manipulation. Items, including "I felt pressured", were rated on a 7-point Likert scale, with labels of 1 (*not at all true*), 4 (*somewhat true*), and 7 (*very true*). The item responses were averaged to provide one score for the subscale. Cooke et al. (2011) reported reliability coefficients ranging from .66 to .90 for this subscale. In this experiment, alpha coefficients in the low and high-pressure conditions during the pre-test and post-test sessions ranged from .66 to .85, demonstrating acceptable internal consistency.

Cortical activity

We recorded EEG activity during the test phase of the experiment from an array of 16 silver/silver chloride pin electrodes on the scalp (Fp1, Fp2, F4, Fz, F3, T7, C3, Cz, C4, T8, P4, Pz, P3, O1, Oz, O2) positioned in accordance with the 10-20 system (Jasper, 1958). The BioSemi EEG system replaces the conventional "ground" electrode with two separate electrodes placed on either side of the vertex: a common mode sense active electrode and a driven right leg passive electrode; the "reference" at the time of recording lies somewhere between these two electrodes. These electrodes form a feedback loop which serves to reduce common mode voltage and thereby increase the signal-to-noise ratio above what would be achieved by systems using conventional ground electrodes with the same impedance (e.g., Metting van Rijn, Peper, & Grimbergen, 1990; see also Biosemi website: http://www.biosemi.com/faq/cms&drl.htm). Electrodes were also placed at the left and right mastoids, to permit offline referencing. All signals were amplified and digitized at 512 Hz with 24-bit resolution (Biosemi ActiveTwo) using ActiView software (Biosemi). Conductive gel (ECI Electro-gel) was applied to all recording electrodes, and all sites were abraded using a blunt needle (for sites on the scalp) and a combination of abrasive paste (Nuprep) and alcohol wipes (Mediswab) (for the mastoids) prior to electrodes being attached.

Performance

Mean radial error was used as our measure of performance, as described above.

Procedure

The protocol was approved by the local research ethics committee. Participants attended five 2-h testing sessions (i.e., pre-test, acquisition 1, acquisition 2, acquisition 3, post-test) on separate days (to prevent any confounding effects of fatigue), with each session being an average of 2.3 ($SD = 2.7$) days apart. In the pre-test session, participants were briefed, instrumented to allow the recording of cortical activity and provided with instructions about the golf-putting task. Specifically, they were asked to try to get all putts "ideally in the hole, but if unsuccessful, to make them finish as close to the hole as possible." Next, they performed 20 familiarization putts to become accustomed to the putting surface and to putting while instrumented for EEG recordings. After the familiarization block, participants performed two blocks of 50 putts, which represented the low- and high-pressure conditions. Each block was preceded by its respective pressure manipulation as described above. After each putt, a photograph was taken to record the terminal location of the ball, and then the ball was replaced at the start position by the experimenter. This ensured that participants did not need to move between trials, thereby keeping movement artefacts to a minimum, while also regulating the time between putts, which approximately ranged from 15 to 30 s. The manipulation check (i.e., pressure/tension subscale of Intrinsic Motivation Inventory, as described above) was administered immediately after the final putt in each of the pressure conditions, while cortical activity was recorded continuously during each block. On completion of the pre-test, participants were thanked and reminded of the time and date of their acquisition sessions.

In the acquisition phase of the experiment, participants were welcomed to the laboratory and instrumented with the neurofeedback system. During the first acquisition session, they were asked to address and fixate on a golf ball for five seconds. This procedure was repeated five times in order to calculate their average baseline high-alpha power. Customized computer scripts were then prepared for each participant in the neurofeedback group in order to set the neurofeedback tone to silence when high-alpha power was reduced from their individual baseline by 26.8%, 53.6%, and 80.4%, in acquisition sessions one, two, and three, respectively. Participants were then issued with the following instructions:

> "The computer will play a tone that is linked to your brain activity. When you reach a prescribed level of brain activity, the tone will turn off. We would like you to produce this level of brain activity before you putt, so we want you to address the ball and get ready to putt, and then wait for the tone to turn off before executing your stroke. You will receive 1-h of neurofeedback training today in the form of 12 blocks of the tone being played for 5-min at a time. During each 5-min block, you will putt as many balls as is permitted in the time, which will depend on the number of times that you manage to turn the tone off. It does not matter how many balls you putt."

Participants then completed the twelve 5-min blocks of putts, interspersed with 2-min breaks between each block. After each putt a photograph was taken to record the terminal location of the ball (e.g., Neumann & Thomas, 2008). In acquisition sessions two and three, participants were instrumented, reminded of their instructions, and immediately began the 12 blocks of putts (i.e., the baseline high-alpha measure only occurred during acquisition session 1). At the end of each session participants were thanked and reminded of the time and date of their next visit. We decided to fix the amount of exposure to the tone (rather than fix the number of putts) because we wished to standardize the amount of experience with the feedback stimulus. By standardizing exposure our neurofeedback training protocol was consistent with other recent neurofeedback studies (e.g., Rostami et al., 2012).

After completing the acquisition phase of the experiment, participants attended the post-test session, which was identical to the pre-test. On completion of the post-test, participants were thanked and debriefed. Upon completion of the study, leaderboards were emailed to participants and competition winners were contacted and paid their prize money.

Data reduction

Individual trials within the continuous cortical recordings were identified using an optical sensor (Datasensor S51-PA 2-C10PK), which detected the initiation of putts, and a microphone (Rode NT1) connected to a mixing desk (Studiomaster Club 2000), which detected the putter-to-ball contacts. These signals were recorded using both Actiview (Biosemi) and Spike2 (Cambridge Electronic Design) software.

Processing of EEG data recorded during the test phase of the experiment was conducted with EEGLab software (Delorme & Makeig, 2004) using the following procedure: First, datafiles were resampled (256 Hz), filtered (1–50 Hz) and referenced to the average mastoid. Next, a neutral EEG baseline was identified (cf., Babiloni et al., 2008). Specifically, we performed a fast Fourier transform (1 Hz bins, Hanning window taper) spanning 7 s before until 1 s after initiation of each putt. We then performed exploratory analyses to identify a period within this 8 s window during which cortical activity was similar across both between (i.e., group) and within-subjects factors (i.e., session and pressure). Specifically, potential baselines were initially identified by eye and then subjected to a series of 2 Group $\times$ 2 Session $\times$ 2 Pressure ANOVAs to verify the absence of main or interaction effects which, if present in the baseline, would confound our interpretation of subsequent results. ANOVAs confirmed no main or interaction effects for high-alpha power in the period from 0 ms to 200 ms around movement, so we selected this window as a neutral baseline, before proceeding with the remaining data processing steps as follows: First, we created new epochs spanning 5 s before until 1 s after each putt (e.g., Babiloni et al., 2008), and performed baseline removal (i.e., subtracted power during the baseline period from power in the other epochs). Next, we screened the data to reject any artefacts. Gross artefacts were removed by rejecting any large deviations in the signal (>100 μV) from the baseline level. This important preprocessing step (see Onton, Westerfield, Townsend, & Makeig, 2006) was followed by independent component analyses, which, in combination with the ADJUST algorithm (Mognon, Jovicich, Bruzzone, & Buiatti, 2011), were used to identify and remove remaining artefacts including eye blinks, eye movements, and the blood pressure pulse. Next, we performed a fast Fourier transform (1 Hz bins, Hanning window taper) on the artefact-free epochs, and averaged the data in successive 1 s epochs from 4 s before (i.e., preparatory period) until 1 s after (i.e., movement period) the initiation of putts. Finally, we computed power in the high-alpha (10–12 Hz) frequency band.

For brevity of reporting, only the results from the key Fz electrode, and those in its immediate surroundings (i.e., F3, F4, Cz) are presented. We selected these electrodes because they roughly overlie the primary motor cortex, the premotor cortex, and the supplementary motor areas that are related to movement control (e.g., Ashe, Lungu, Basford, & Lu, 2006), and which have been

implicated in previous EEG-based golf-putting research (Babiloni et al., 2008). Moreover, these electrode sites captured the strongest effects, and were largely representative of the other sites.

Statistical analyses

Performance and number of putts struck in the acquisition phase of the experiment were subjected to 2 Group × 3 Session × 12 Block Analyses of Variance (ANOVAs). Measures of cortical activity during the test phase were subjected to 2 Group × 2 Session × 2 Pressure × 5 Epoch (i.e., −4 to −3 s, −3 to −2 s, −2 to −1 s, −1 s to 0 s, 0 s to +1 s) ANOVAs. Finally, the pressure manipulation check and performance recorded during the test phase were subjected to 2 Group × 2 Session × 2 Pressure ANOVAs. These analyses were designed to assess the three aims of our experiment as explained in the results section. Significant effects were probed by polynomial trend analyses and planned post hoc comparisons. The results of univariate tests are reported, with the Huynh-Feldt correction procedure applied to analyses, which violated the sphericity of variance assumption. Partial eta-squared is reported as a measure of effect size, with values of .02, .12, and .26 indicating relatively small, medium, and large effect sizes, respectively (Cohen, 1992).

Results

Acquisition phase

Analyses of the measures obtained in the acquisition phase of the experiment allowed us to indirectly assess whether neurofeedback taught participants to produce expert like cortical activity (i.e., number of putts struck) and promoted expedited learning.

Number of putts struck

A 2 Group (neurofeedback, control) × 3 Session (acquisition 1, acquisition 2, acquisition 3) × 12 Block ANOVA performed on the number of putts struck during acquisition revealed effects of both session, $F(2, 44) = 44.73$, $p < .001$, $\eta_p^2 = .67$, $\varepsilon = .85$, and block, $F(11, 242) = 7.41$, $p < .001$, $\eta_p^2 = .25$, $\varepsilon = .62$, as well as a session × block interaction, $F(22, 484) = 24.10$, $p < .05$, $\eta_p^2 = .11$, $\varepsilon = .52$. Planned comparisons indicated that participants completed fewer putts in the final acquisition session than in the earlier acquisition sessions. The effect of block was best characterised by a linear polynomial trend ($p < .001$, $\eta_p^2 = .46$), with participants hitting more putts in those blocks at the end of each session compared to those at the start. Finally, the session × block interaction reflected differences in the linear trend for block ($p < .05$, $\eta_p^2 = .21$), which was strongest in session 1 and weakest in session 3. Importantly, there were no effects of group and no group × session or group × block interactions, indicating that: a) all participants completed a similar number of putts during the acquisition phase; b) participants in the neurofeedback group achieved greater control of the tone, as indexed by them completing more putts as the blocks within each session progressed; and c) the tone was more difficult to turn off as the high-alpha power thresholds were made progressively more difficult, as indexed by participants completing fewer putts in the final acquisition session. These data are illustrated in Fig. 1A.

Performance

A 2 Group (neurofeedback, control) × 3 Session (acquisition 1, acquisition 2, acquisition 3) × 12 Block ANOVA conducted on mean radial error during the acquisition phase revealed main effects of both session, $F(2, 44) = 12.40$, $p < .001$, $\eta_p^2 = .36$, $\varepsilon = .89$, and block, $F(11, 242) = 6.71$, $p < .001$, $\eta_p^2 = .23$ Participants decreased their mean radial error from the first training session to the subsequent sessions. The effect of block was best characterised by a linear polynomial trend ($p < .001$, $\eta_p^2 = .53$), with participants tending to decrease their mean radial error from the blocks at the start of each acquisition session to blocks at the end. There were no effects of group, and there were no interactions. These data are illustrated in Fig. 1B.

Test phase

Analyses of the measures obtained in the test phase of the experiment allowed us to directly assess whether neurofeedback taught participants to produce expert like cortical activity and promoted expedited learning. They also allowed us to assess whether neurofeedback encouraged consistent patterns of cortical activity and robust performance across both low and high levels of pressure.

Cortical activity

Separate 2 Group (neurofeedback, control) × 2 Session (pre-test, post-test) × 2 Pressure (low, high) × 5 Epoch (i.e., −4 to −3 s, −3 to −2 s, −2 to −1 s, −1 s to 0 s, 0 s to +1 s) ANOVAs were employed to examine EEG high-alpha power. These analyses revealed no main effects of group or pressure. However, main effects of epoch, $Fs(4, 88) = 4.08–5.52$, $ps < .001$, $\eta_p^2 s = .16 – .20$, $\varepsilon s = .90–.94$, and session, $Fs(1, 22) = 11.97–14.02$, $ps < .01$, $\eta_p^2 s = .35 – .39$, were revealed at all sites. The effects of epoch were best characterised by cubic polynomial trends ($ps < .001$, $\eta_p^2 s = .45 – .53$), while the effects of session indicated that high-alpha power was lower in the post-test ($Ms = −0.04–0.07$, $SDs = 1.02–1.19$ Δ power) than in the pre-test ($Ms = 0.88–1.00$, $SDs = 0.84–0.88$ Δ power).

Crucially, we also found group × session interactions at all sites, $Fs(1, 22) = 6.35–10.77$, $ps < .05$, $\eta_p^2 s = .22 – .33$. Planned comparisons revealed that high-alpha power was reduced from the pre-test to the post-test in members of the neurofeedback group, but not in members of the control group. The group × session interaction at the Fz site (representative of all sites) is illustrated in Fig. 2.

Finally, we found epoch × pressure interactions at Fz, $F(4,58) = 2.75$, $p < .05$, $\eta_p^2 = .11$, $\varepsilon = .86$, and F4, $F(4,58) = 2.69$, $p < .05$, $\eta_p^2 = .11$, $\varepsilon = .81$. These interactions reflected pressure differences in the cubic trends ($ps < .05$, $\eta_p^2 s = .20 – .22$), which were stronger in the high-pressure condition than in the low-pressure condition. In brief, high-alpha power was slightly greater in the early phases of preparation (i.e., −4 s to −1 s) in the high-pressure condition. The epoch × pressure interaction at the Fz site (also representative of the effect at F4) is illustrated in Fig. 3.

Performance

A 2 Group (neurofeedback, control) × 2 Session (pre-test, post-test) × 2 Pressure (low, high) ANOVA performed on mean radial error during the test phase revealed a main effect of session, $F(1, 22) = 38.54$, $p < .001$, $\eta_p^2 = .64$. Participants decreased their mean radial error from the pre-test (Neurofeedback group $M = 20.20$, $SD = 9.00$ cm; Control group $M = 19.33$, $SD = 4.62$ cm) to the post-test (Neurofeedback group $M = 15.89$, $SD = 7.43$ cm; Control group $M = 14.91$, $SD = 5.15$ cm). There were no effects of group or pressure and there were no interactions.

Pressure manipulation check

A 2 Group (neurofeedback, control) × 2 Session (pre-test, post-test) × 2 Pressure (low, high) ANOVA for self-reported pressure confirmed a main effect for pressure, $F(1, 22) = 37.32$, $p < .001$, $\eta_p^2 = .63$. Perceived pressure increased from the low-pressure condition ($M = 2.70$, $SD = 0.95$) to the high-pressure condition ($M = 3.59$, $SD = 0.96$), confirming that our pressure manipulation

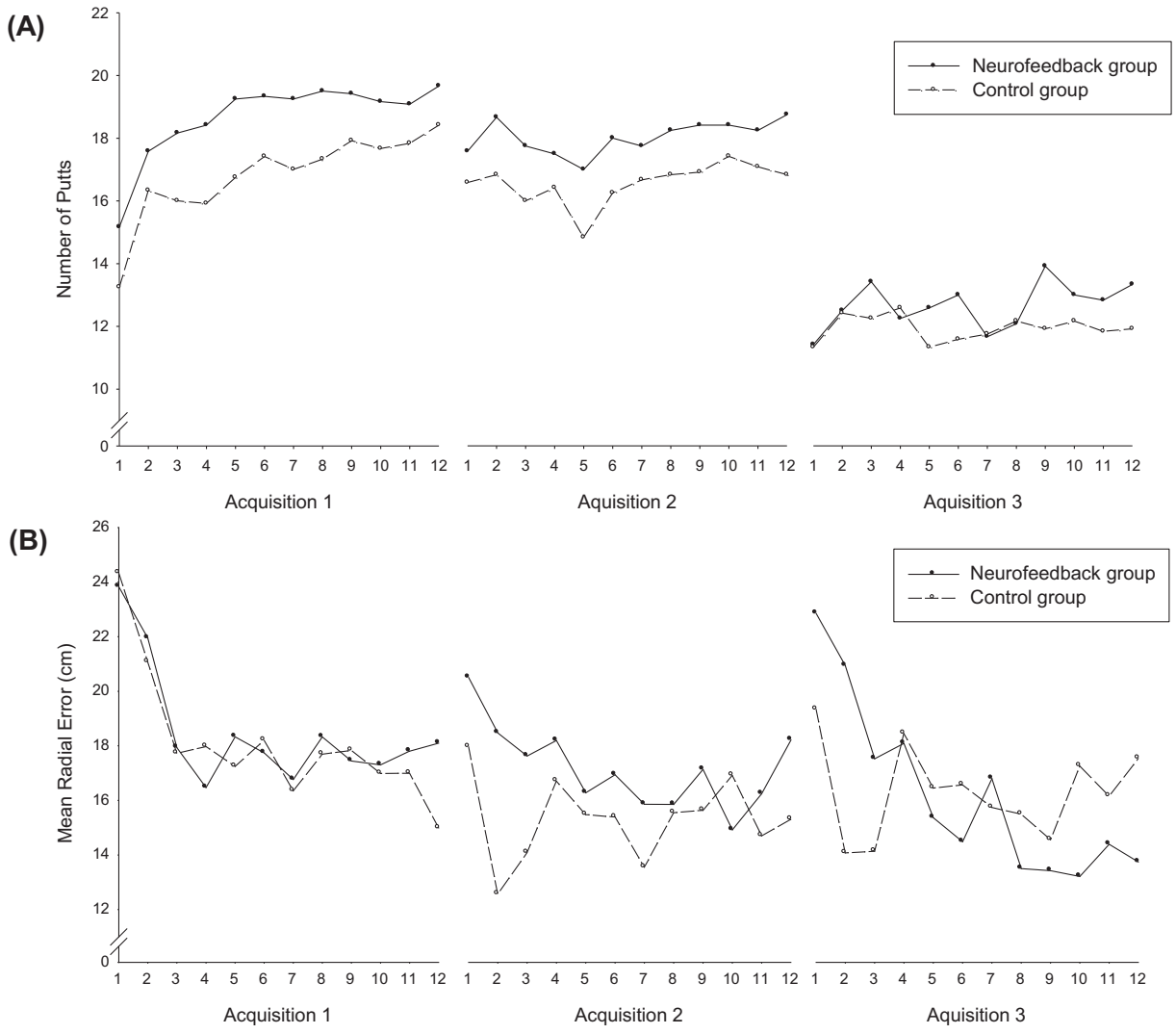

Fig. 1. (A) Number of putts executed during each block in the acquisition phase of the experiment. (B) Mean radial error during each block in the acquisition phase of the experiment.

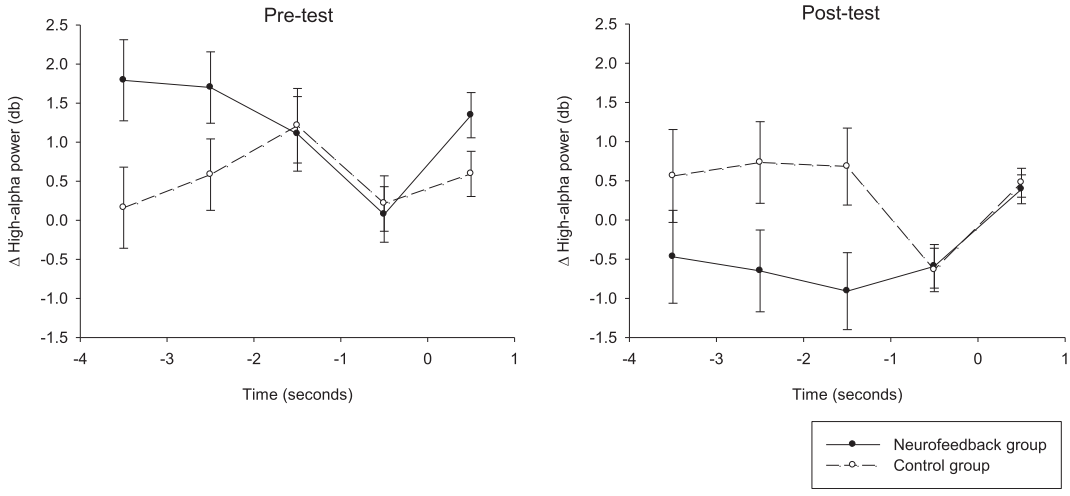

Fig. 2. Group × session interaction for high-alpha power at the Fz site (representative of all sites). Error bars depict standard error of the means.

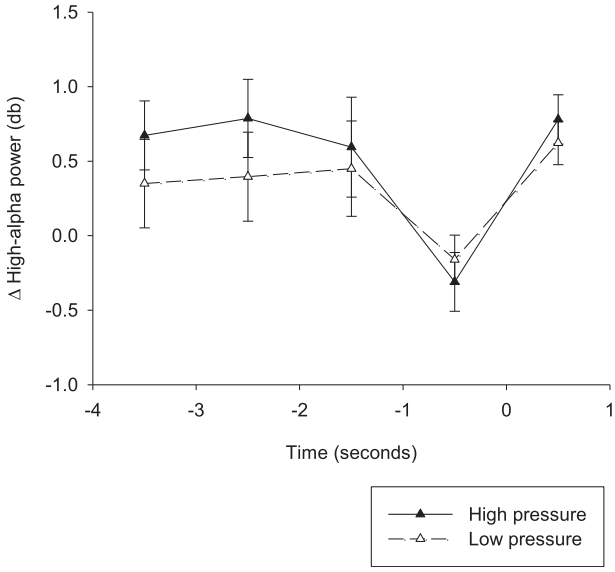

Fig. 3. Epoch × pressure interaction for high-alpha power at the Fz site (representative of all sites). Error bars depict standard error of the means.

was successful. There were no effects of group or session, and there were no interactions.

Discussion

Neurofeedback training offers the exciting possibility of expedited motor skill acquisition, and, thus, more efficient development of excellence and expertise in sport (Gruzelier, Egner, & Vernon, 2006). This experiment is one of the first to empirically investigate the effectiveness of neurofeedback training as a tool to accelerate learning in sport. Our aims were to: a) examine whether neurofeedback training could teach recreational golfers to produce the patterns of brain activity that are exhibited by experts in the moments preceding successful putts; b) evaluate whether neurofeedback training could improve performance and thereby accelerate the novice to expert evolution; and c) examine whether neurofeedback training could help produce patterns of cortical activity and performance levels that would be robust to the potential deleterious effects of increased psychological pressure. Our results are discussed in the sections that follow.

Effects of neurofeedback training on cortical activity

We supported our hypothesis that neurofeedback training would be successful in teaching recreational golfers to suppress frontal high-alpha power during preparation for putting. First, in the acquisition phase of the experiment, we revealed an effect of block, indicating that participants were able to complete more putts in five minutes in those blocks towards the end of each training session compared to those at the start. This provides indirect evidence that the neurofeedback group learned to reduce high-alpha power and thereby turn off the neurofeedback tone more frequently as the blocks in each training session progressed. Second, we provided the first direct evidence of neurofeedback training leading to selective changes in cortical activity, as implied by the group by session interactions for EEG high-alpha power at frontal sites. Specifically, members of the neurofeedback group reduced their pre-movement high-alpha power from the pre-test to the post-test, whereas members of the control group did not. This key finding clearly reveals for the first time that relatively brief neurofeedback training (i.e., 3 h over three separate days) can teach recreational golfers to regulate their cortical activity even when the source of neurofeedback (i.e., the auditory tone) has been removed.

Effects of neurofeedback training on performance

Our hypothesis that neurofeedback training would facilitate performance and thereby expedite the development of expertise was not supported. Although members of the neurofeedback group learned how to suppress their high-alpha power in the moments preceding putts, their performance during acquisition and the improvement in their mean radial error score from the pre-test to the post-test were similar to the improvements achieved by members of the control group. This separation between cortical activity and behavioural outcome could indicate that reduced pre-movement high-alpha power is not a key determinant of golf-putting success. However, based on the evidence provided by Babiloni et al. (2008) and Cooke et al. (2014), this conclusion seems unlikely. There are three alternative explanations that could reconcile this discrepancy.

First, it must be conceded that the pattern of high-alpha power that our neurofeedback group learned to produce was not entirely representative of the activity that is produced before the successful putts of experts. Specifically, our participants produced a general suppression of high-alpha power spanning the entire four second preparatory period, whereas experts have been shown to produce a sharp decline in high-alpha power that is most evident during the final two seconds before and during movement (Cooke et al., 2014). It is thus possible that a dynamic reduction in high-alpha power (i.e., event-related desynchronisation) is required in order to deliver putting success (e.g., Babiloni et al., 2008). However, to counter this claim, our neurofeedback group produced a dynamic reduction in pre-movement high-alpha in the pre-test, yet they performed worse than in the post-test, where a dynamic reduction was absent (Fig. 2). Similarly, the control group produced a dynamic reduction in high-alpha power in both pre-test and post-test sessions, but this did not yield better performances than the neurofeedback group.

A second alternative is that the method employed to elicit the pre-movement reduction in high-alpha power is important for putting success, rather than the reduction in high-alpha power per se. For example, it is well-established that high-alpha power has an inverse relationship with cortical activity, such that a decrease in high-alpha power reflects heightened activation (e.g., Pfurtscheller, 1992). Accordingly, it would have been possible for the recreational golfers in our study to learn that they could reduce their high-alpha power and thereby turn off the neurofeedback tone by engaging in a number of cognitive activities that are irrelevant to golf putts (e.g., Nowlis & Kamiya, 1970). In contrast, one may speculate that expert golfers produce their reduction in high-alpha power by engaging specific working memory processes in order to programme movement parameters such as direction and force (e.g., Cooke, 2013). To counter this suggestion, one could argue that if members of our neurofeedback group were engaging in irrelevant activities to turn off the neurofeedback tone, their performance is likely to have been impaired. Nevertheless, it would be useful for future studies to examine the precise strategies that expert golfers use to produce reductions in pre-movement high-alpha power. The outcomes of such studies could provide cues to help ensure that participants regulate their cortical activity by engaging in the same processes as experts in future neurofeedback interventions.

Finally, it is possible that it is a suppressed absolute level of high-alpha power in those seconds immediately preceding and during movement (i.e., −2 s to +1 s) that is the key to expertise and putting success (e.g., Babiloni et al., 2008; Cooke et al., 2014). In the

present study, neurofeedback training led to suppressed high-alpha power early during movement preparation, but in the final second before and during movement the high-alpha power of the neurofeedback group and the control group was the same (Fig. 2). This seems the most likely explanation for the null effect of neurofeedback training on performance in our experiment. It could be attributed to our neurofeedback tone being silenced for 1.5 s once the prescribed high-alpha power threshold had been breached (cf. Arns et al., 2007). This afforded the possibility for participants to begin to increase high-alpha power in the final moments before and during movement, while the neurofeedback tone remained turned off. This potential artefact could be remedied in future studies by removing a pre-set silence duration once the neurofeedback threshold is achieved.

Effects of neurofeedback on cortical activity and performance under pressure

Our final hypothesis was that neurofeedback training would help promote consistent preparatory cortical activity and performances under both low and high levels of pressure. We found that performance levels remained robust for both the neurofeedback and the control groups, so neurofeedback training failed to yield any selective benefits for performance during pressured conditions. The null effects of pressure on performance could be attributed to the high number of trials that were required to generate meaningful EEG data (e.g., Luck, 2005). Specifically, it is known that multiple trials dilute the strength of pressure manipulations, in this case providing participants with several chances to redeem bad putts, and likely eliciting levels of pressure far below those experienced in real-life (Cooke et al., 2010; Woodman & Davis, 2008). Future studies should afford special consideration to methods of maximising the impact of the pressure manipulations, especially when large numbers of trials are planned.

Finally, in contrast to our hypothesis, we found that neurofeedback training failed to inoculate participants against pressure-induced changes in cortical activity. Elevated pressure served to increase the change in high-alpha power over time at sites overlying frontal regions of the cortex (i.e., Fz, F3) in both groups of participants. Given that high-alpha power is inversely related to cortical activity (e.g., Pfurtscheller, 1992), increased high-alpha power during the early phases of motor preparation in the high-pressure condition could reflect worrisome thoughts diverting attentional resources away from the motor planning (i.e., frontal) regions of the brain (Fig. 3). It is possible that more training sessions were required in order for the volitional control of cortical activity to outweigh the involuntary changes that appear to be induced by increases in psychological stress.

Limitations and future directions

In addition to the potential limitations of the neurofeedback protocol outlined above, we concede that the sample size was relatively small. However, the sample size was larger than those adopted in relevant previous studies (e.g., Arns et al., 2007 $N = 6$; Landers et al., 1991 $N = 16$). Moreover, our study was sufficiently powered to detect a number of main and interaction effects as detailed above. Notwithstanding, it may be beneficial for future studies to replicate and extend our experiment with a larger cohort.

Future research would also do well to investigate other aspects of cortical activity, such as EEG coherence neurofeedback training. In brief, EEG coherence analyses assess the degree of linear interrelatedness between signals recorded at two sites, with high coherence commonly thought to represent functional communication between the two sites (e.g., Thatcher, Krause, & Hrybyk, 1986). To this end, it has recently been suggested that a reduction in coherence between the left-hemispheric verbal-analytic regions (e.g., electrode site T3) and the motor planning regions (e.g., electrode site Fz) of the brain represent a reduction in verbal-analytic information processing, and characterise successful performance across golf putting, rifle shooting and surgical laparoscopy tasks (e.g., Deeny, Hillman, Janelle, & Hatfield, 2003; Zhu, Poolton, Wilson, Hu, et al., 2011; Zhu, Poolton, Wilson, Maxwell, & Masters, 2011). This understanding of what T3-Fz coherence reflects presents researchers with a first opportunity to supplement neurofeedback with coaching strategies (e.g., implicit learning techniques – see Masters & Poolton, 2012; Zhu, Poolton, Wilson, Maxwell, & Masters, 2011; Zhu, Poolton, Wilson, Hu, et al., 2011) to help ensure that trainees produce the desired "expert-like" coherence patterns through relevant methods. Such a cross-pollination of training methods could increase the likelihood of neurofeedback yielding expedited learning and robust performances under stress (e.g., Zhu, Poolton, Wilson, Hu, et al., 2011; Zhu, Poolton, Wilson, Maxwell, & Masters, 2011).

Finally, future research should also carefully investigate the mechanisms which underpin the expected beneficial effects of neurofeedback training on performance. For instance, researchers could conduct source localisation analyses to more precisely identify the individual brain structures that are responsible for generating the EEG activity measured at the scalp. This would offer insight into the physiological mechanisms of excellence. Alternatively, researchers could conduct statistical mediation analyses to verify proposed causal relationships among cortical, cardiac, somatic and motor systems. We were unable to perform such analyses here because neurofeedback failed to produce selective benefits for performance.

Conclusion

In conclusion, this is the first experiment to show that brief neurofeedback training (i.e., 3 h) can teach recreational golfers to regulate their cortical activity during a retention test. Importantly, and in line with the themes of this special issue, these results provide proof of principle that neurofeedback training can be used to alter cortical activation, thereby providing further support for the notion that this technique can help expedite the development of expertise in athletes. Neurofeedback training failed to yield any selective benefits for performance in the present study. This could be explained by limitations of our neurofeedback protocol as outlined above. By refining neurofeedback protocols and furthering our understanding of the cortical correlates of expertise, future studies could expedite development of expertise and excellence, and neurofeedback can increasingly feature in motor learning protocols in the years and decades to come.

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